

Physics with Tau Leptons at CDF

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On behalf of the CDF Collaboration

Wine and Cheese Seminar - July 23, 2004

Outline:

- Physics topics
- CDF Detector
- Taus at CDF
- Results, analyses in progress
- Summary and Outlook

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The Tau Lepton

- Third generation; charged: $Q^\tau = \pm 1$
- Heavy: $m_\tau = 1.777 \text{ GeV}$
- Decays :
 - Leptonic: $\tau \rightarrow e \bar{\nu}_e \nu_\tau, \tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$ ($\sim 36\%$)
 - Hadronic: $\tau \rightarrow \pi \nu_\tau, \tau \rightarrow \pi \pi^0 \nu_\tau, \tau \rightarrow \pi \pi \pi \nu_\tau, \tau \rightarrow \pi \pi^0 \pi^0 \nu_\tau \dots$ ($\sim 64\%$)
→ rich decay spectrum!
- Why use taus?
 - Many SUSY models predict enhanced couplings to third-generation particles (b, τ)
 - Important for MSSM Higgs search, other SUSY particles at the Tevatron and beyond

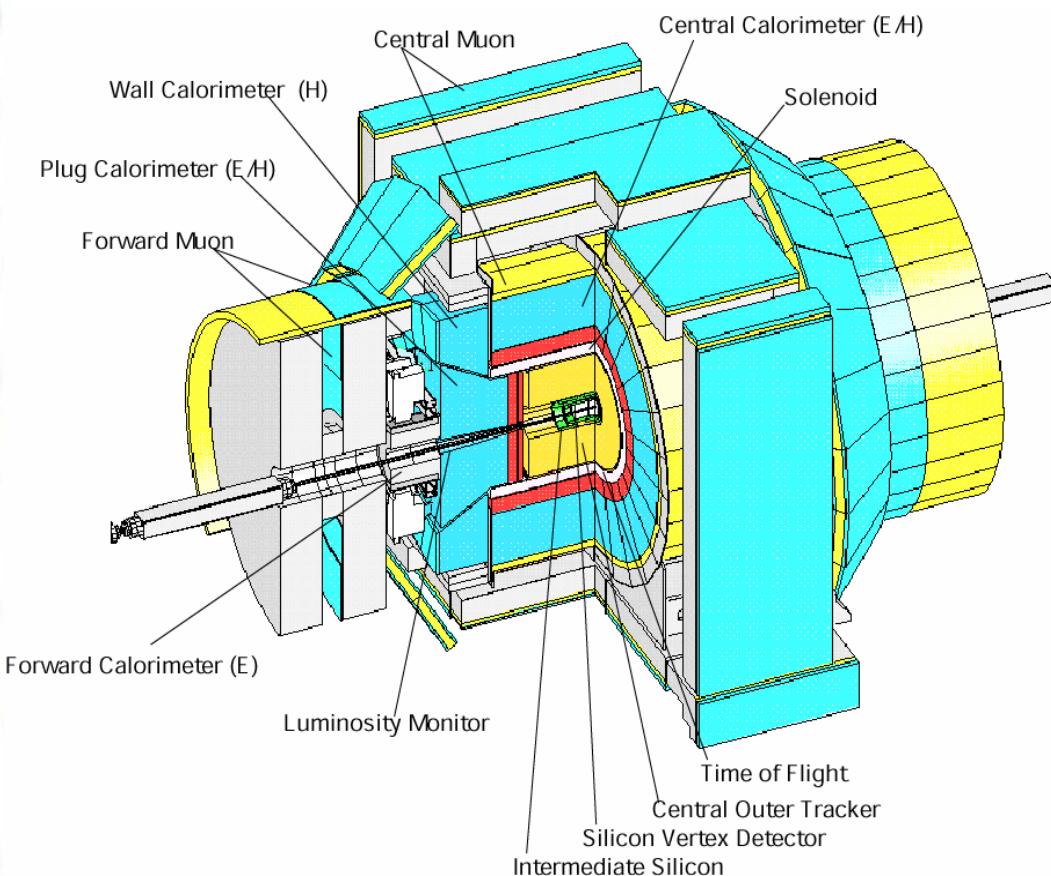
Valuable tool for new physics searches!

Throughout this talk we use τ_e, τ_μ, τ_h as shorthand notations for $\tau \rightarrow e \bar{\nu}_e \nu_\tau, \tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$, and $\tau \rightarrow \text{hadrons} \nu_\tau$, respectively.

Physics Topics at a Glance

- Measurements:
 - $\sigma(p\bar{p} \rightarrow W) \cdot BR(W \rightarrow \tau\nu)$, $BR(W \rightarrow \tau\nu)/BR(W \rightarrow e\nu)$
 - $\sigma(p\bar{p} \rightarrow Z) \cdot BR(Z \rightarrow \tau\tau)$
- Searches:
 - MSSM Higgs
 - Other “high-mass” particles decaying to $\tau\tau$
 - Anomalous production of $t \rightarrow q\tau\nu$
 - Prospects for SUSY searches with τ 's:
 - R-parity Violating (RPV) stop
 - Minimal Super-Gravity (mSUGRA) with tri-lepton final states
 - Trileptons in Gauge Mediated SUSY Breaking (GMSB) models

The CDF Detector at the Tevatron



- Multipurpose detector for studying products of $p\bar{p}$ collisions
- Tracking: SVX and Wire Chambers
- Calorimetry: EM, Hadronic
- Shower Maximum for EM
- Pre-shower Radiators
- Muon Detectors
- TOF System

Taus at CDF in Run 2

- Build on the experience from Run 1
- Dedicated tau triggers in Run 2:

Require a “narrow isolated jet” object (τ_h)

Must be tau-like:

Cluster-Matched track with $p_T > 4.5 \text{ GeV}$,
no tracks with $p_T > 1.5 \text{ GeV}$ in isolation annulus $10-30^\circ$

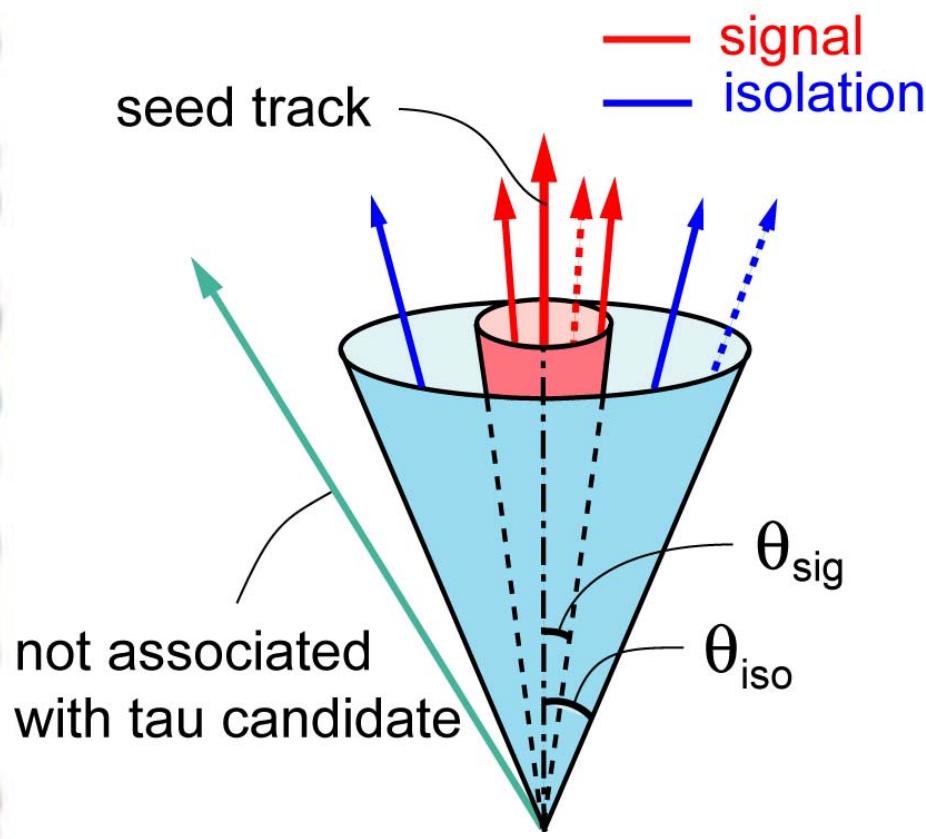
- **Electron + τ_h (~30 nb at L3)**
 - Central electron ($E_T > 8 \text{ GeV}$) + narrow isolated jet
- **Muon + τ_h (~30 nb at L3)**
 - Central muon ($p_T > 8 \text{ GeV}$) + narrow isolated jet
- **Missing Transverse Energy + τ_h (~5 nb at L3)**
 - $\cancel{E}_T > 20 \text{ GeV}$ + narrow isolated jet
- **Di-tau: $\tau_h + \tau_h$ (~13 nb at L3)**
 - Two narrow, isolated jets
- **A committed Tau Working Group serves as a driving force for analyses using tau leptons.**

Taus at CDF: Reconstruction

Refers to reconstruction of the visible products of semi-hadronic tau decays

- Taus in the detector: narrow isolated jets
- Tau “objects” formed using calorimeter and tracking information
 - Seed tower with $E_T > 6 \text{ GeV}$
 - Adjacent towers added to form a calorimeter cluster with $N^{\text{twr}} \leq 6$
 - Matched (seed) track with $p_T > 4.5 \text{ GeV}$
 - Tracks and π^0 's around seed track added to be used in tau reconstruction isolation

Taus at CDF: Identification

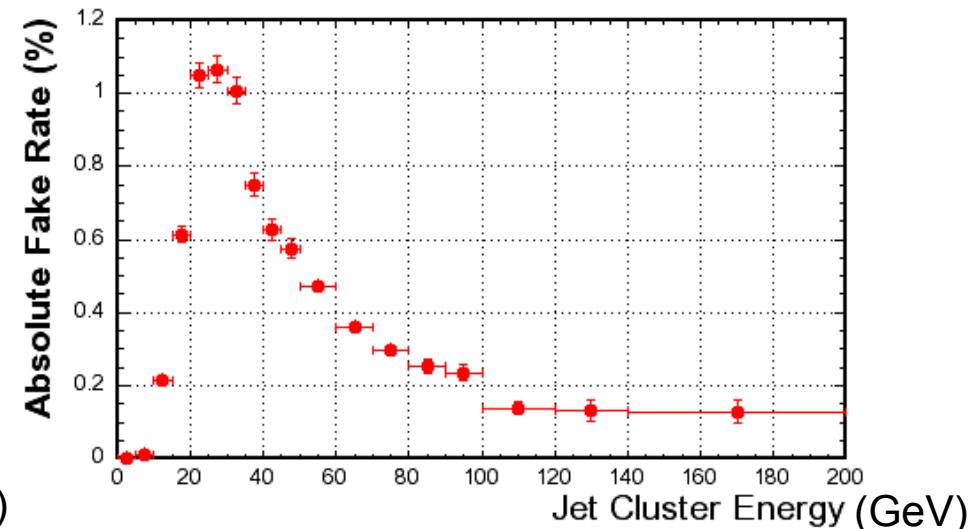
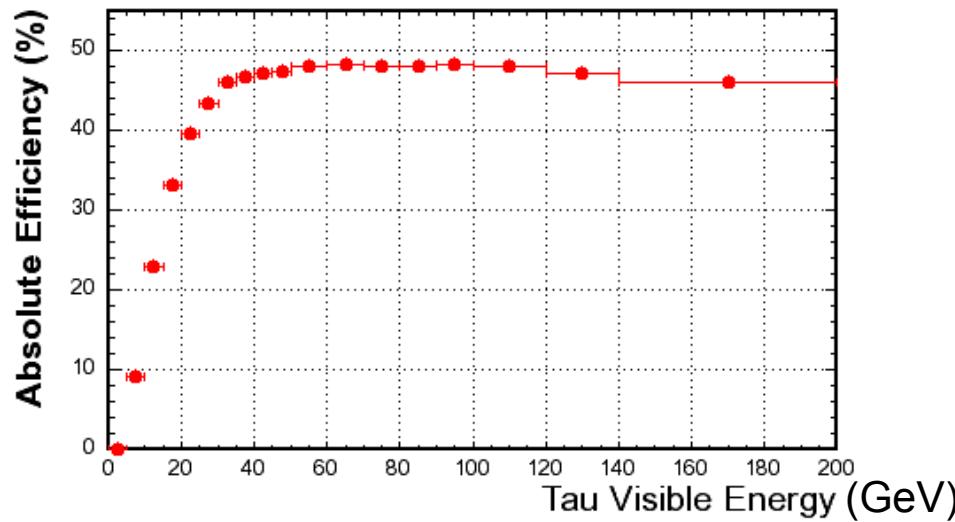


Successfully reconstructed taus have:

- Characteristic 1,3 track enhancement in signal cone
- Net charge 1
- Low π^0 multiplicity
- $m < 1.8 \text{ GeV}$
- No energetic tracks, π^0 's in isolation annulus
- Applied electron removal

Taus: efficiency and jet $\rightarrow\tau$ fake rate

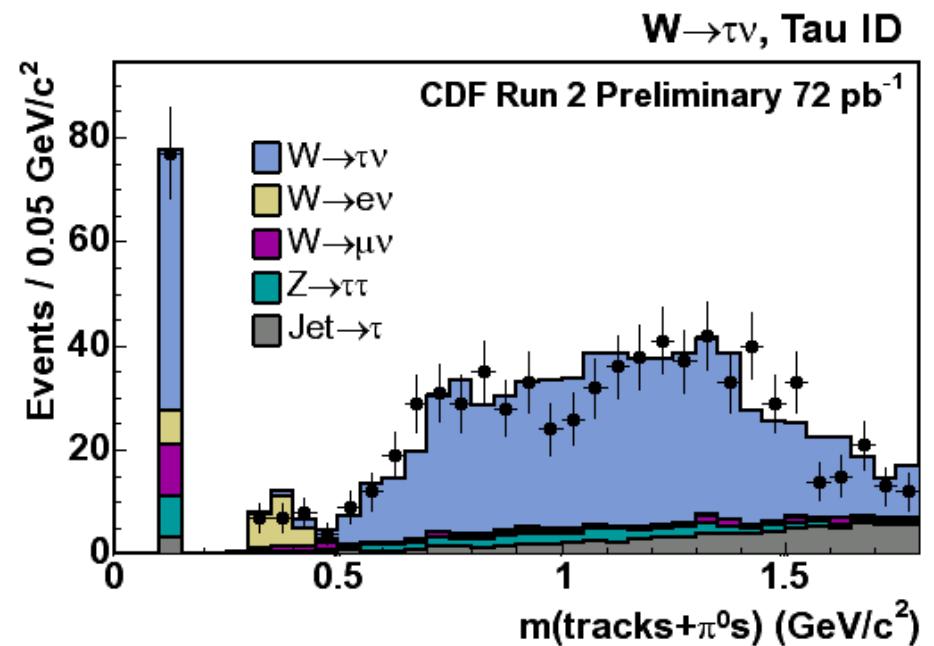
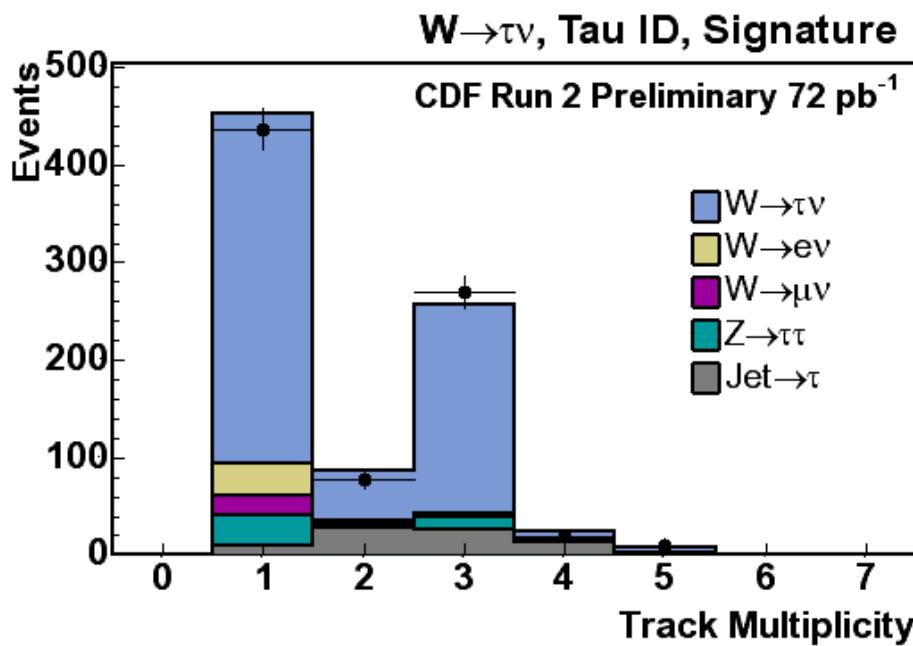
- Depend on tau isolation applied (analysis specific)
- Example** efficiency and fake rate:



(Examples from the high-mass $\tau\tau$ search)

Clean tau sample from $W \rightarrow \tau\nu$

- W's are the largest source of isolated taus at CDF
- Select clean τ sample: large E_T , veto extra jets
- Natural choice for understanding tau reconstruction

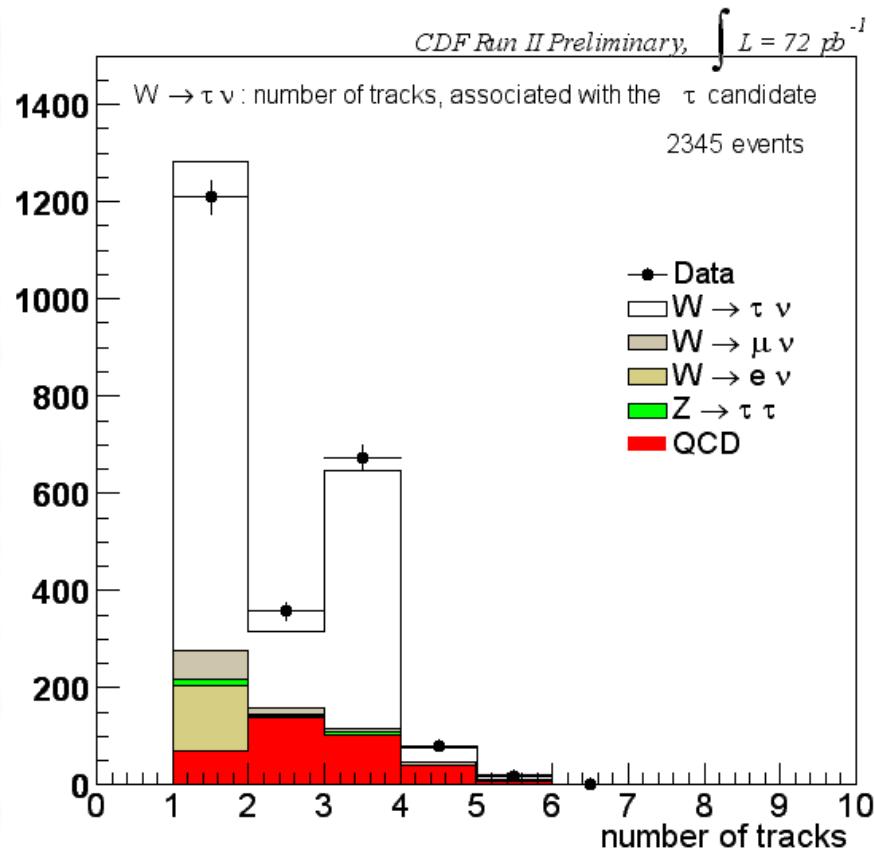


- Good agreement between data and MC simulation

Study of $W \rightarrow \tau\nu$

- Measurement of:
 - $\sigma(pp \rightarrow W) \cdot BR(W \rightarrow \tau\nu)$
 - $BR(W \rightarrow \tau\nu) / BR(W \rightarrow e\nu)$
 - Test lepton universality via g_τ/g_e
 - Uses the “tau + MET” trigger
 - Selection criteria:
 - Isolated tau candidate with $E_T > 25$ GeV
 - No other jet with $E_T^{\text{jet}} > 5$ GeV
 - Missing transverse energy: $\cancel{E}_T > 25$ GeV
 - Electron removal
- Major backgrounds: $\text{jet} \rightarrow \tau$ misidentification, $Z \rightarrow \tau\tau$
 $W \rightarrow \mu\nu, e\nu$

Study of $W \rightarrow \tau\nu$ (cont.)



- $N_{\text{obs}} = 2345$
- $N_{\text{bg}}^{\text{tot}} = 612 \pm 61$
- $A \cdot e_{\tau}^{\text{ID}} = (1.06 \pm 0.047(\text{stat}) \pm 0.043(\text{syst}))\%$
- Trigger efficiencies:
 - $\varepsilon(L1) = 0.881 \pm 0.005$
 - $\varepsilon(L3) = 0.982 \pm 0.004$

Cross section (nb):

$$\sigma(p\bar{p} \rightarrow W) \cdot \text{BR}(W \rightarrow \tau\nu) = 2.62 \pm 0.07(\text{stat}) \pm 0.21(\text{syst}) \pm 0.16(\text{lum})$$

Systematics limited!

Study of $W \rightarrow \tau\nu$ (cont.)

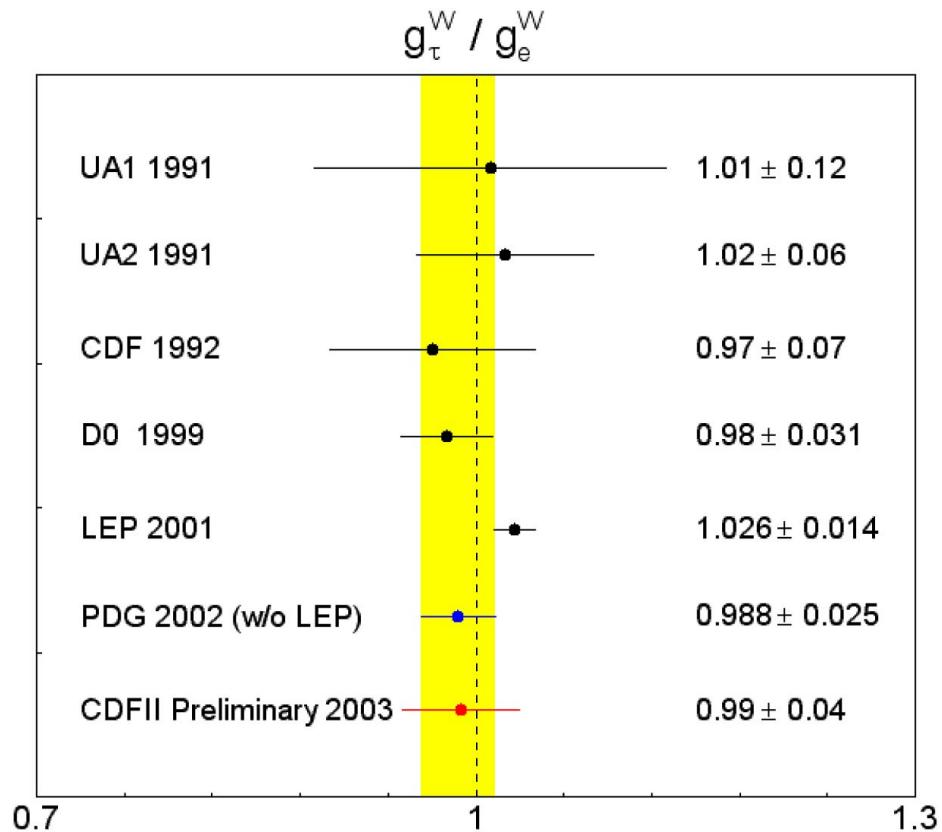
- $\text{BR}(W \rightarrow \tau\nu)/\text{BR}(W \rightarrow e\nu)$ measurement
 - Large $W \rightarrow e\nu$ sample
 - Common systematics are cancelled
 - Can use same trigger as the tau channel

$$\text{BR}(W \rightarrow \tau\nu)/\text{BR}(W \rightarrow e\nu) = 0.99 \pm 0.04(\text{stat}) \pm 0.07(\text{syst})$$

$$g_\tau/g_e = \sqrt{\text{BR}(W \rightarrow \tau\nu)/\text{BR}(W \rightarrow e\nu)}$$

$$g_\tau/g_e = 0.99 \pm 0.02(\text{stat}) \pm 0.04(\text{syst})$$

Study of $W \rightarrow \tau\nu$ (cont.)



- Very competitive result
- Consistent with SM
- Still dominated by systematics:
 - Tau ID
 - Background estimation

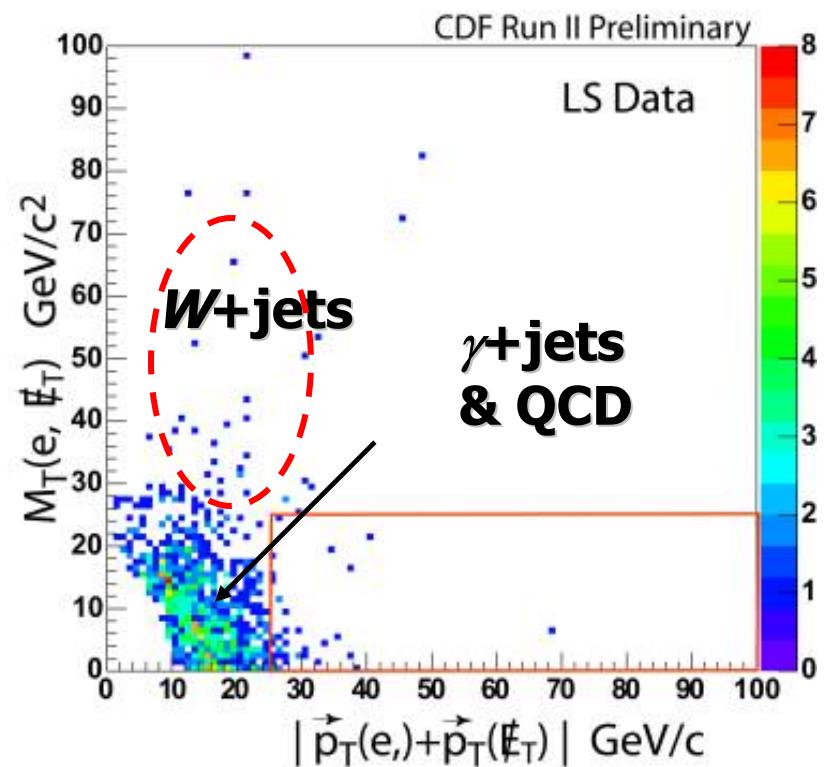
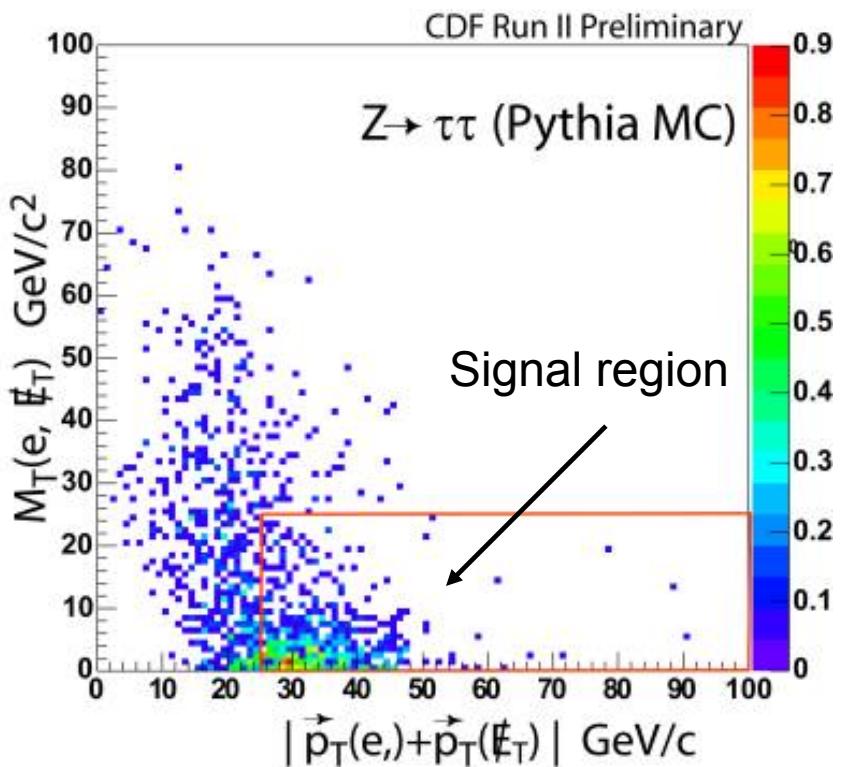
Work on reducing the systematics is converging.
Updated result coming soon!

Measurement of $\sigma(p\bar{p} \rightarrow Z) \cdot BR(Z \rightarrow \tau\tau)$

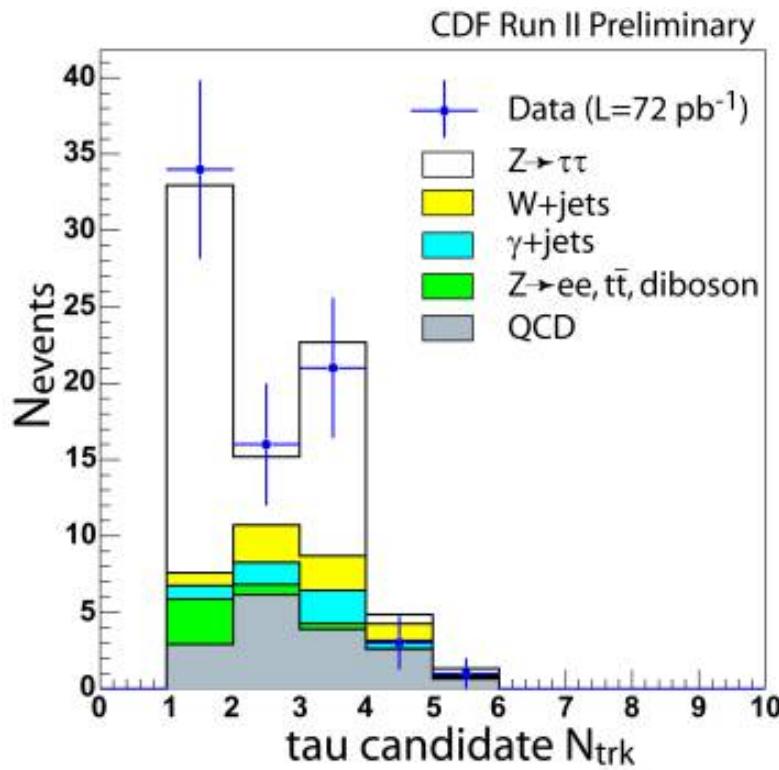
- Z's are the second-largest source of isolated taus
- No (published) Z cross-section measurement in tau channel from hadron collider
- Major background in new physics searches
- Many techniques for background suppression and estimation apply to SUSY searches
- The presented result is based on 72 pb^{-1} of data
- Look at $\tau_e \tau_h$ channel
- Events selected with the “electron+track” trigger

$Z \rightarrow \tau\tau$ Study: Selection Criteria

- Isolated τ , electron
- $P_T^\tau > 15$ GeV
- $E_T^e > 10$ GeV
- $p_T(e, \bar{E}) > 25$ GeV
- $m_T(e, \bar{E}) < 25$ GeV
- $Q^e Q^\tau = -1$; $N_{trk} = 1, 3$



$Z \rightarrow \tau\tau$ Study: Observed Events



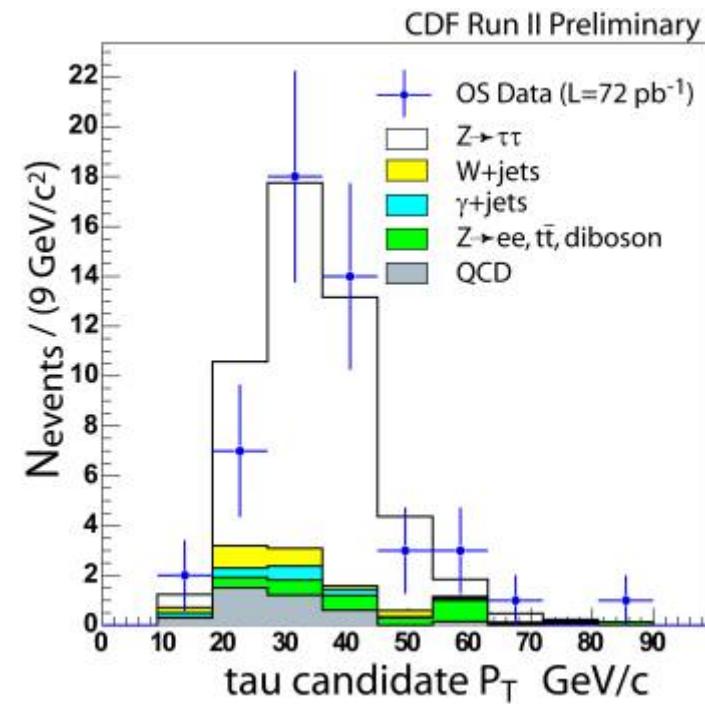
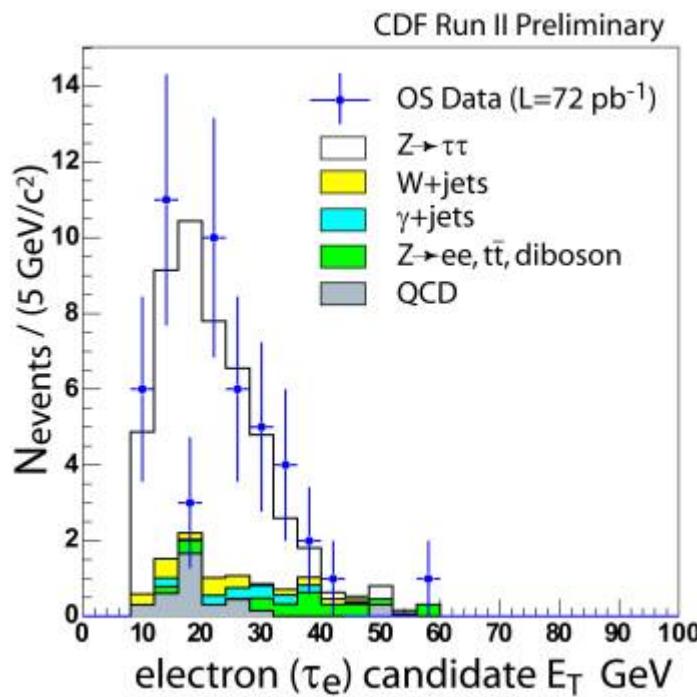
Track multiplicity of tau candidates before opposite charge requirement.

- Clear tau signature
- Backgrounds under control even before $Q^e Q^\tau = -1$
- Charge and track multiplicity clean the sample significantly



$Z \rightarrow \tau\tau$ Study: Observed Events

Electron E_T and tau p_T distributions after all cuts



Relatively low E_T^e and $p_T^\tau \rightarrow Z$ will cause trouble in SUSY searches and need to be well understood.

$Z \rightarrow \tau\tau$ Study: Results and Prospects

- Observe total of 50 events, 39 signal
- Measured cross-section (pb):

$$\sigma(p\bar{p} \rightarrow Z) \cdot BR(Z \rightarrow \tau\tau) = 242 \pm 48(\text{stat}) \pm 26(\text{syst}) \pm 15(\text{lum})$$

- Consistent with measurements in $Z \rightarrow ee$, $\mu\mu$ channels
- Statistics limited

Next steps:

- Add available data
- Include channel with one tau decaying to muon and neutrinos

Searches for New Particles Decaying to Tau(s)

- We can do EW measurements with taus
- What about seeing **new** particles?

The Higgs Boson(s)

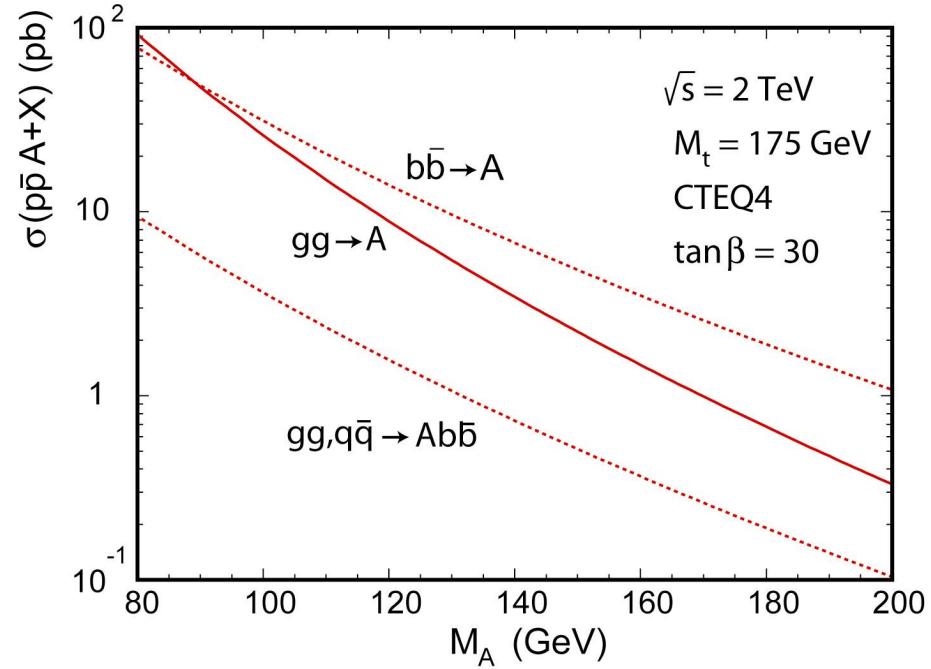
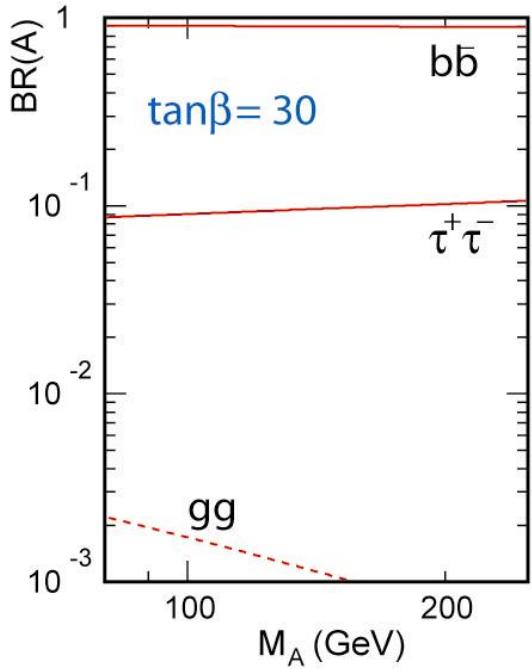
- One of the priorities of Run 2
- However, need large luminosity ($>3\text{-}5 \text{ fb}^{-1}$ for 3σ observation CDF+D0)
- The last SM particle...

... or is it going to be “the first” SUSY particle?

- MSSM:
 - Five physical states: $H, h, A; H^\pm$
 - Enhanced production for large $\tan\beta$
 - $\text{BR}(A \rightarrow \tau^+\tau^-) \sim 8\%$, $\text{BR}(A \rightarrow b\bar{b}) > 90\%$

We could use some help from Nature!

Case for MSSM Higgs $\rightarrow\tau\tau$ Search



- BR($A \rightarrow b\bar{b}$) is larger, *however*, it is difficult to control backgrounds for $gg, b\bar{b} \rightarrow A$
- A $\rightarrow\tau\tau$ is important for MSSM Higgs searches

Higgs $\rightarrow\tau\tau$ Signatures

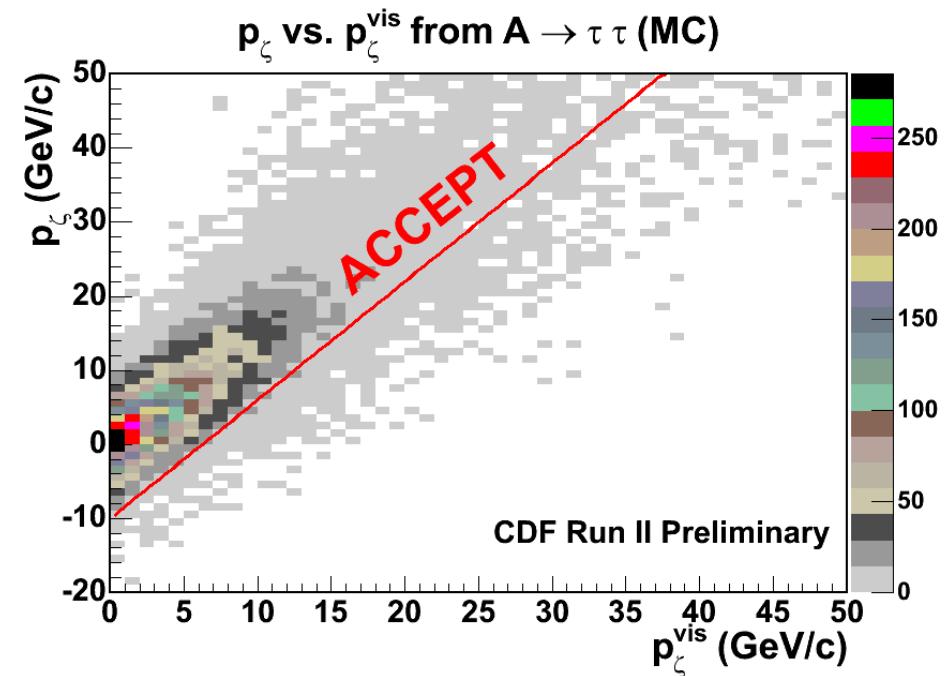
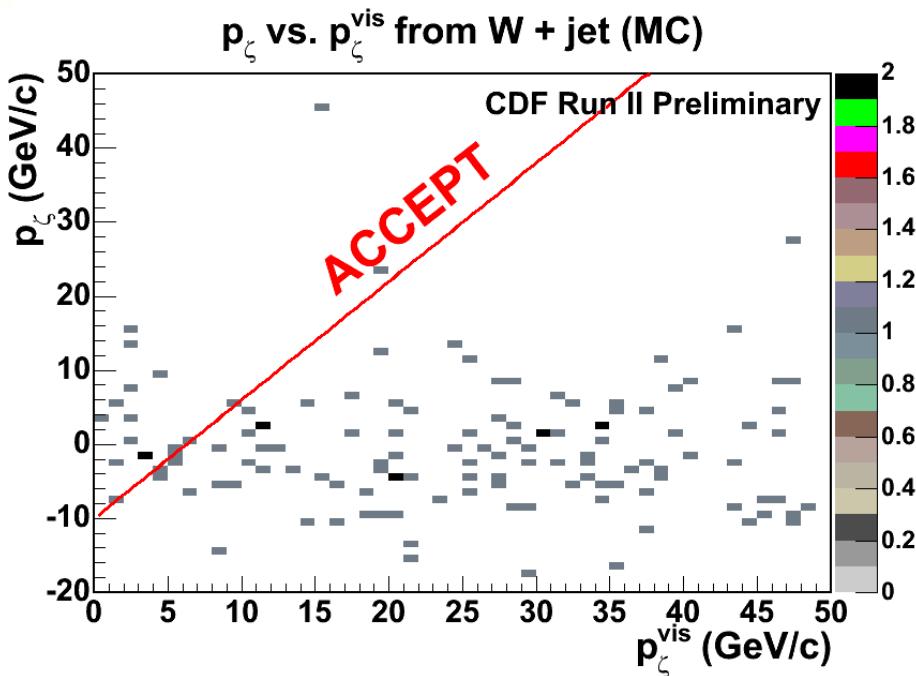
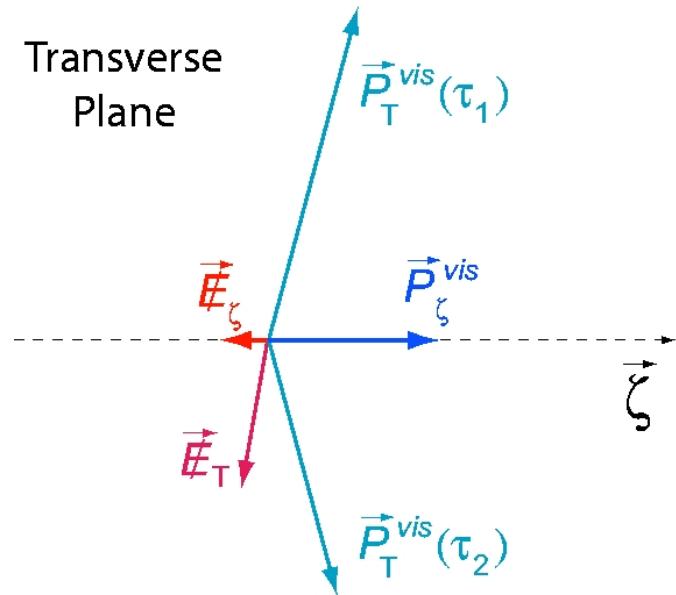
- Determined by the decay modes of the taus

Mode	Fraction (%)	Comment
$\tau_e \tau_e$	3	large $Z/\gamma^* \rightarrow ee$ bg
$\tau_\mu \tau_\mu$	3	large $Z/\gamma^* \rightarrow \mu\mu$ bg
$\tau_e \tau_\mu$	6	low jet backgrounds
$\tau_e \tau_h$	23	golden
$\tau_\mu \tau_h$	23	golden
$\tau_h \tau_h$	41	challenging (jet bg)

Reminder: τ_e , τ_μ , τ_h are shorthand notations for $\tau \rightarrow e\bar{v}v$, $\tau \rightarrow \mu\bar{v}v$, and $\tau \rightarrow hadrons v$, respectively.

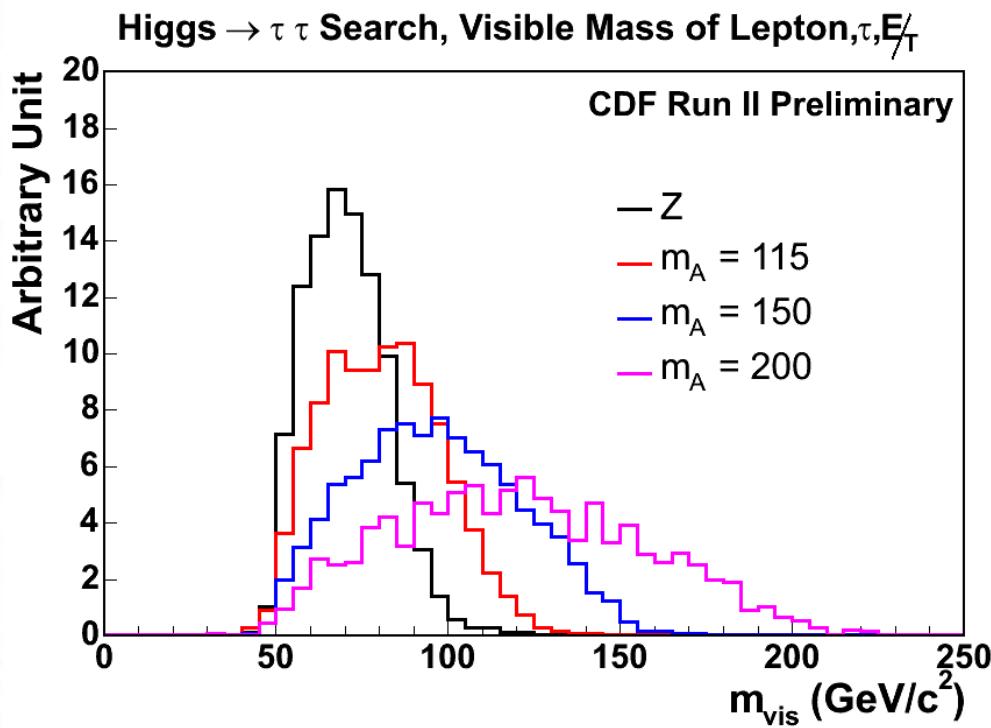
MSSM Higgs Search: Event Selection

- Identify unique e, μ, τ in the event
- Exactly one $\tau_e \tau_h$ or $\tau_\mu \tau_h$ candidate
- Suppress multi-jet bg:
 $|p_T^{\ell}| + |p_T^\tau| + |\cancel{E}_T| > 50 \text{ GeV}$
- Relation between of \cancel{E}_T , $e(\mu)$, and τ
 used to suppress $W \rightarrow \ell \nu + \text{jet(s)}$
 (contributes to jet $\rightarrow \tau$ fakes)



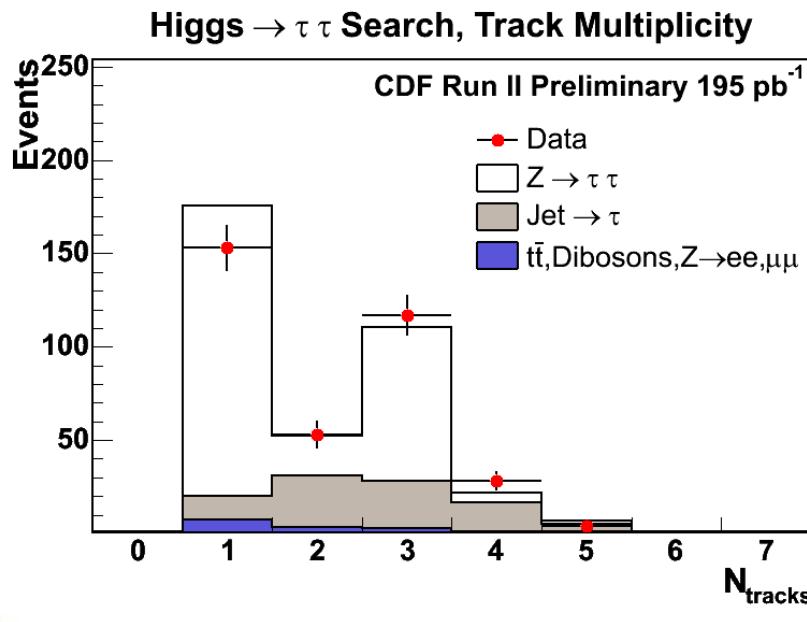
Can we Separate Z and Higgs?

- Not enough information for full mass reconstruction
- Methods using \cancel{E}_T projection onto directions of visible decay products significantly reduce statistics
- Compromise: construct mass-like quantity $m_{\text{vis}}(\ell, \tau, \cancel{E}_T)$



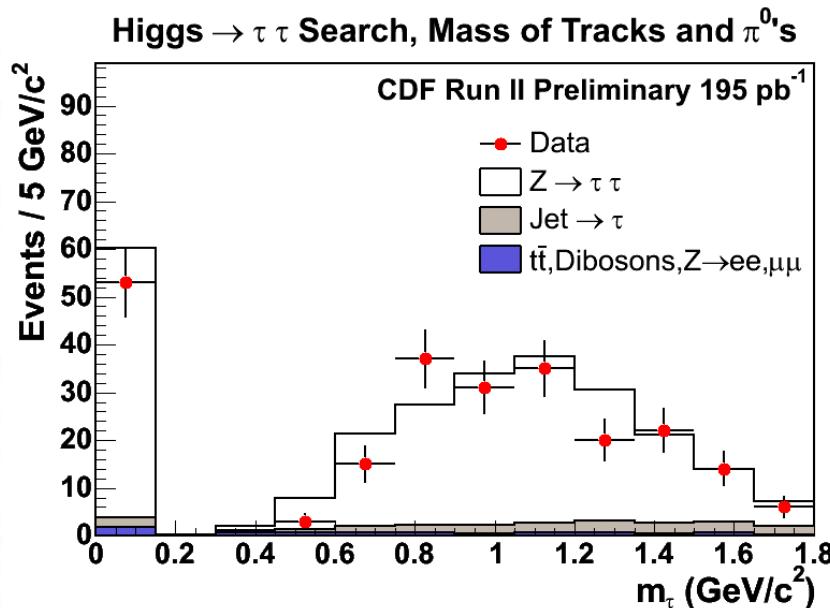
- ✗ Weaker discriminator than full mass
- ✗ Non-linear relation with mass
- ✓ Still, there is substantial non-overlapping region
- ✓ Can be calculated for all events

Higgs Search: Observed Events



$\tau_e \tau_h$ and $\tau_\mu \tau_h$ channels combined:

Track multiplicity of tau candidates before applying
 $N_{\text{trk}}=1,3$ and $Q^\ell Q^\tau = -1$

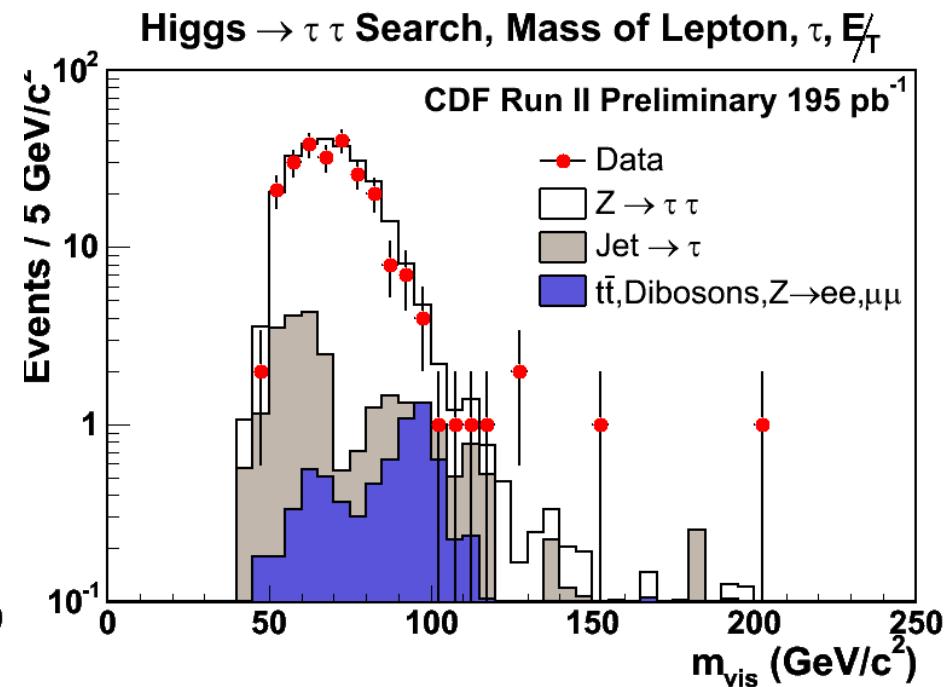
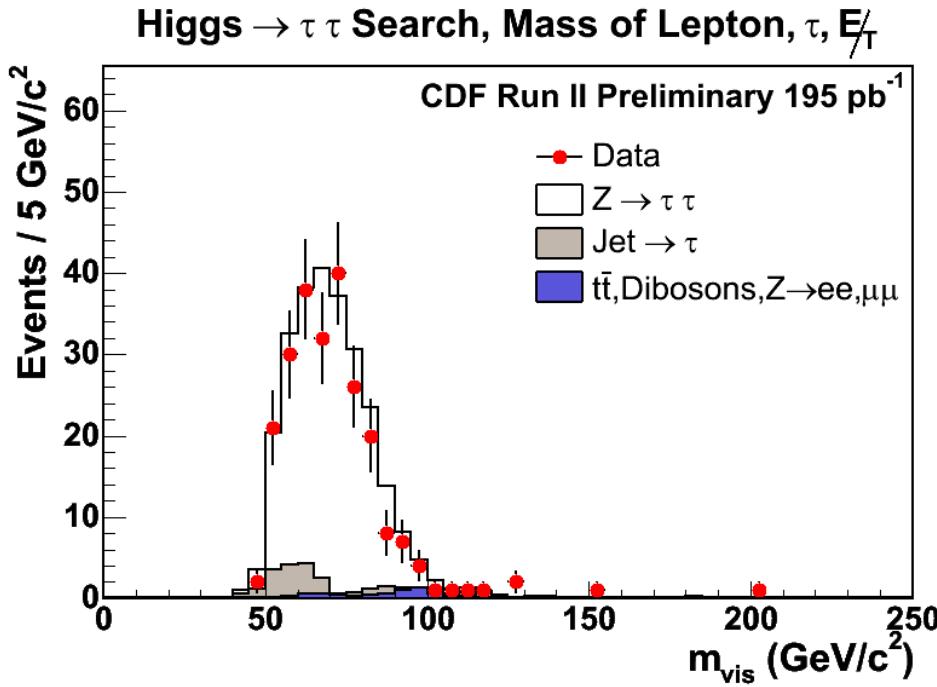


Mass distribution for tau candidates after applying
 $N_{\text{trk}}=1,3$ and $Q^\ell Q^\tau = -1$
(all subsequent plots and have these cuts)

Observed events : 236

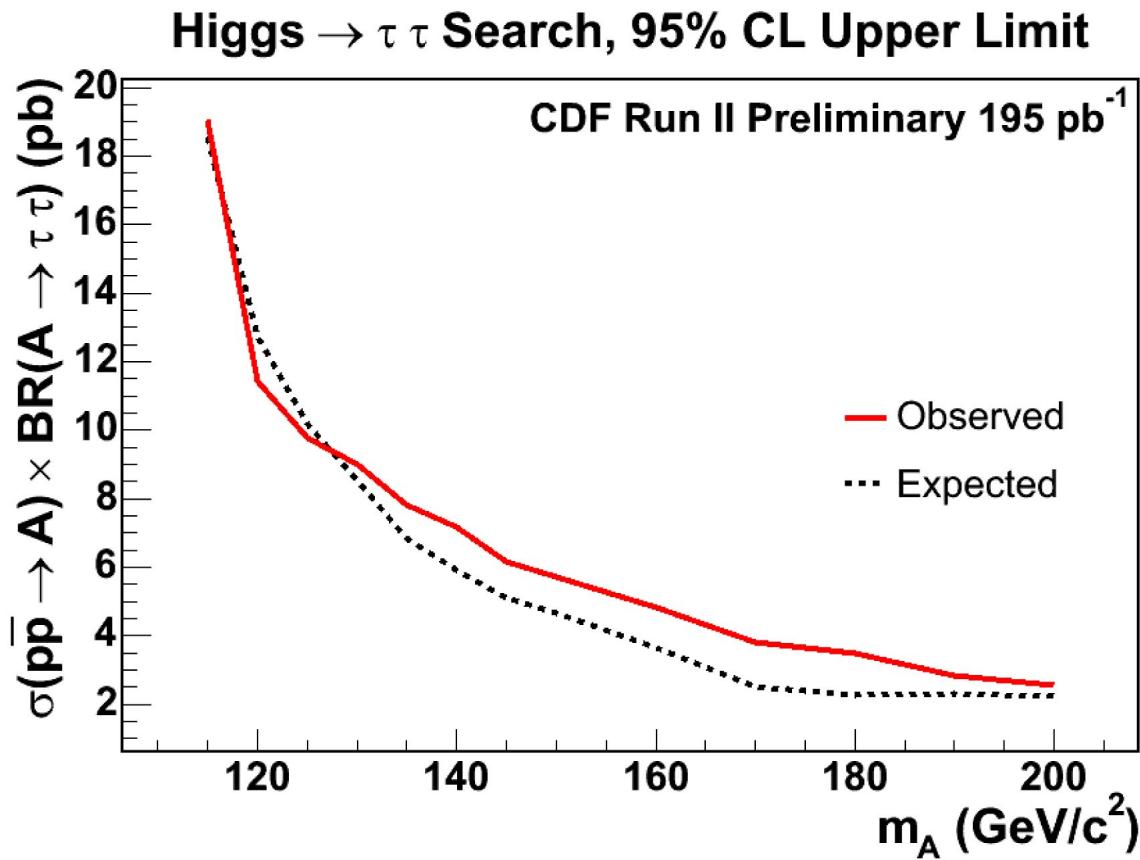
Estimated non $\tau_{e(\mu)} \tau_h$: 27

Higgs Search: $M(\ell, \tau, E_T)$



- The 95% CL upper limits are extracted using a binned likelihood fit of the $m_{\text{vis}}(\ell, \tau_h, E_T)$ distributions
- The observed limits are compared with pseudo-experiment predictions

Higgs Search: 95% CL Upper Limit



- MC generated with $\tan\beta=30$ used in acceptance estimation
- Observed limits fall in the realm of theory predictions for large $\tan\beta$, where Higgs width becomes a factor for acceptance

Higgs $\rightarrow \tau\tau$ Search: What is Next

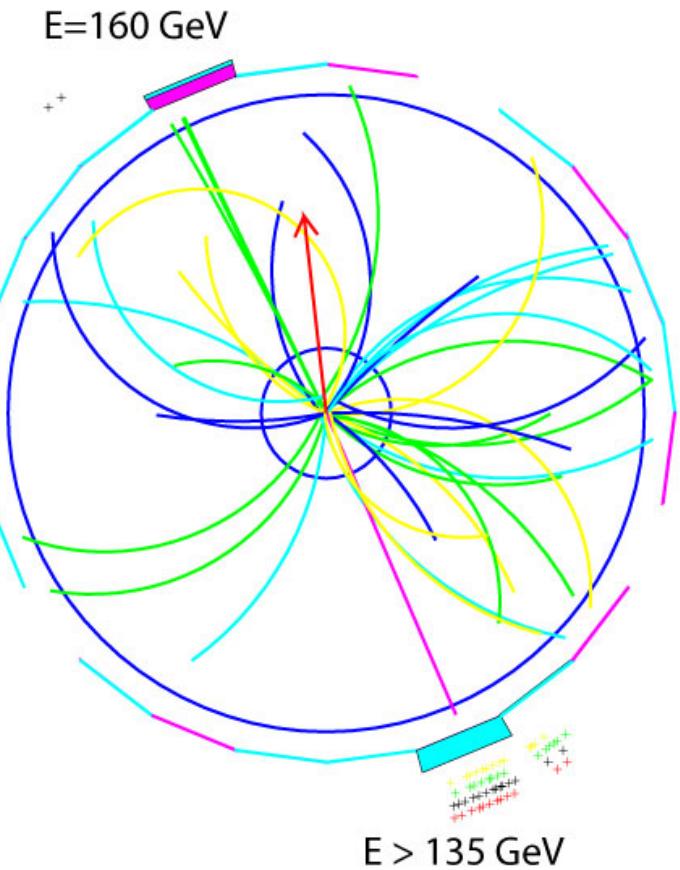
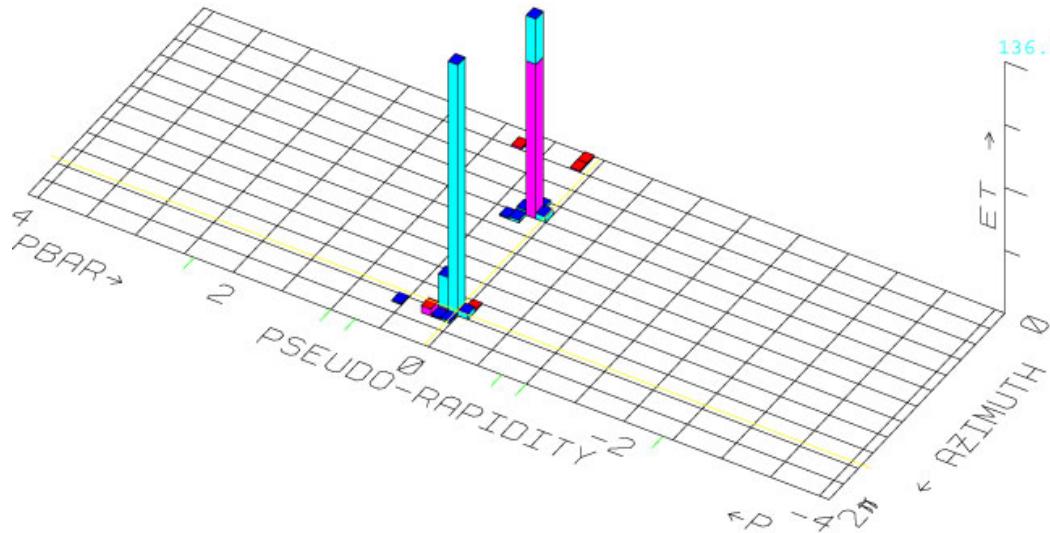
- More data is available
- Add $\tau_e \tau_\mu$ and $\tau_h \tau_h$ channels (clear signatures observed, di-tau trigger efficiency study in progress)
- Some tau reconstruction and event selection optimization
- Include exclusive search for $A b(b)$ (following Willenbrock *et al.*)

Other “High-mass” $\tau\tau$

- Search for Z' with SM couplings, or
- Other exotic particles decaying to tau pairs

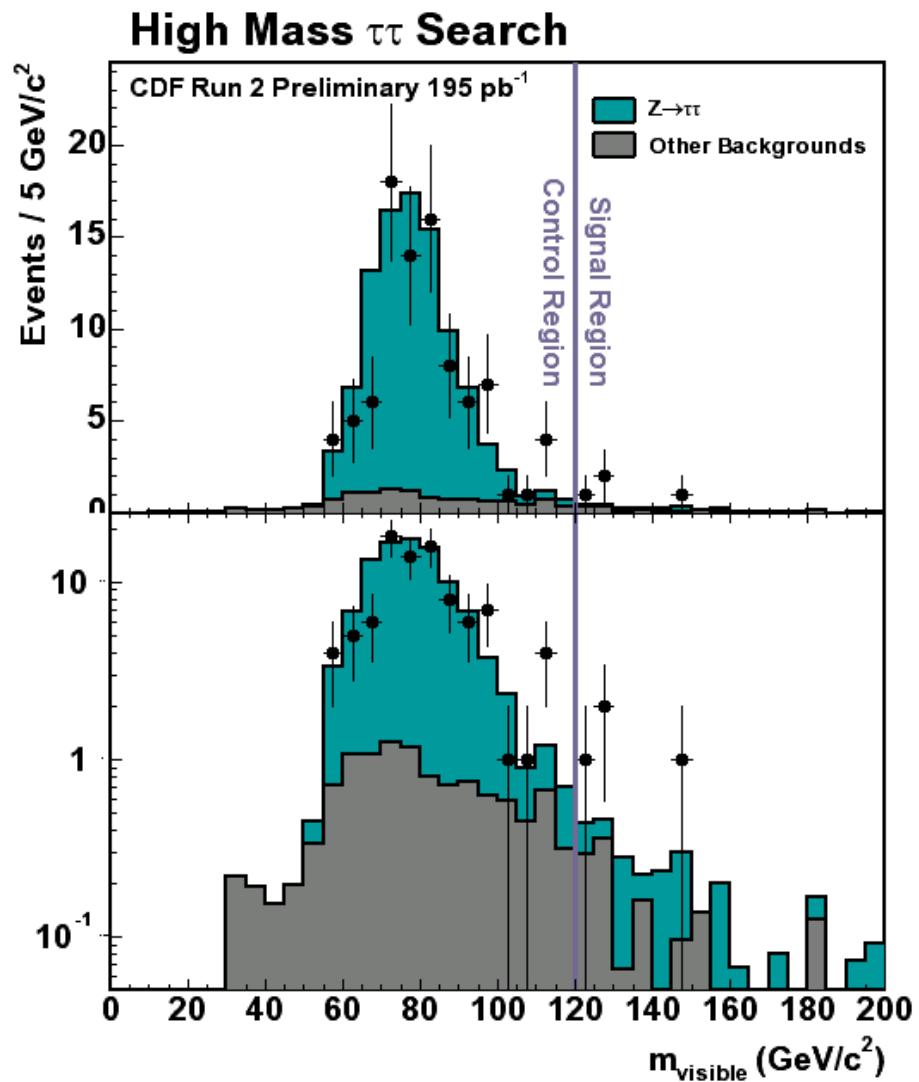
“History”

Run 1 event with two very energetic tau candidates, and E_T .



$Z' \rightarrow \tau\tau$ Search: Event Selection

- Require $\tau_e \tau_h$, $\tau_\mu \tau_h$, or $\tau_h \tau_h$
- $E_T > 15$ GeV
- $|\Delta\phi(\tau_\ell, E_T)| < 30^\circ$
- Suppress $Z \rightarrow \tau\tau$:
 $M(\tau, \tau, E_T) > 120$ GeV
- Blind analysis
 - control region:
 $M(\tau, \tau, E_T) < 120$ GeV
 - Signal region:
 $M(\tau, \tau, E_T) > 120$ GeV
- “Counting experiment”
- Here τ_ℓ is either τ_e , τ_μ , or the lower- p_T τ_h (in $\tau_h \tau_h$ case)



$Z' \rightarrow \tau\tau$ Search: Observed Events

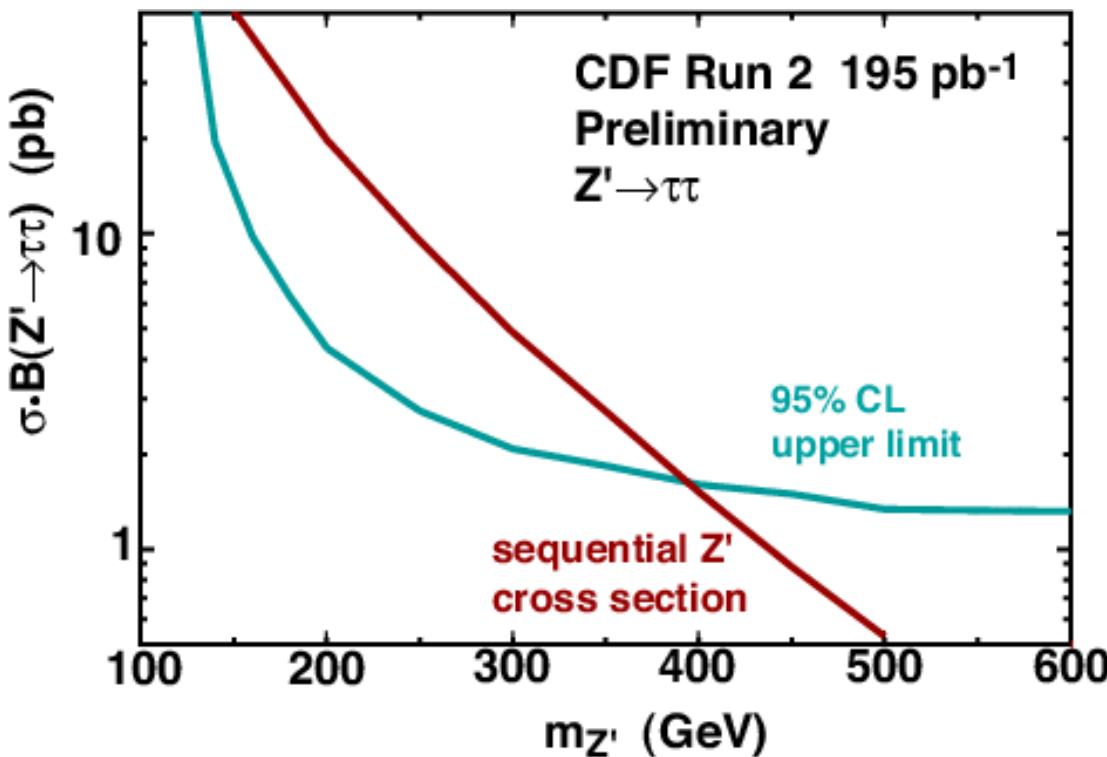
Predicted backgrounds and observed events

CDF Run 2 Preliminary (195 pb⁻¹)

source	$\tau_e \tau_h$	$\tau_\mu \tau_h$	$\tau_h \tau_h$	combined
$Z/\gamma^* \rightarrow \tau\tau$	0.56 ± 0.11	0.50 ± 0.09	0.36 ± 0.08	1.42 ± 0.19
$Z/\gamma^* \rightarrow ee$	0.16 ± 0.14	0	0	0.16 ± 0.14
$Z/\gamma^* \rightarrow \mu\mu$	0	0.50 ± 0.25	0	0.50 ± 0.25
jet $\rightarrow \tau$ fakes	0.29 ± 0.14	0.18 ± 0.09	0.28 ± 0.10	0.75 ± 0.19
Total predicted BG	1.01 ± 0.23	1.18 ± 0.28	0.64 ± 0.13	2.83 ± 0.39
Observed	4	0	0	4

- No significant excess of events observed
- The 95% CL upper limits are extracted as a function of Z' mass

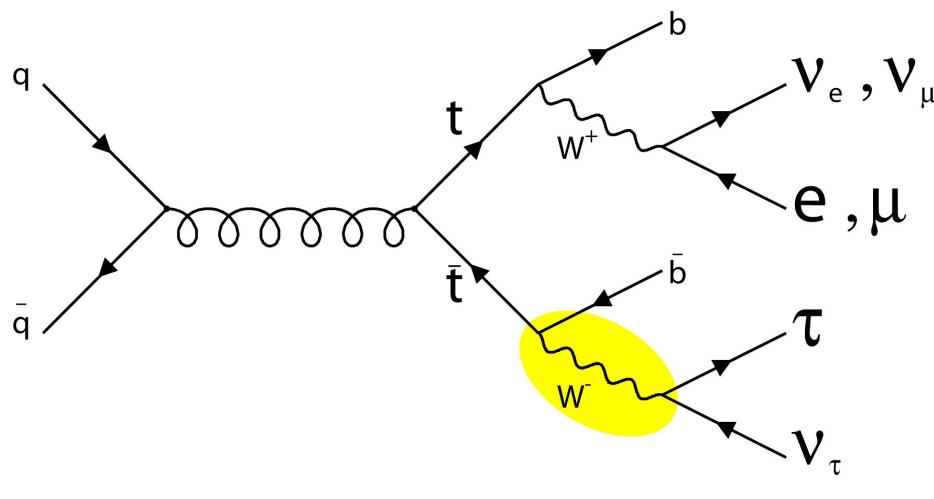
$Z' \rightarrow \tau\tau$ Search: 95% CL Upper Limit



- Z' with SM couplings used in estimating acceptance
- Sequential Z' boson with mass below 394 GeV is excluded at 95% CL

Further development: Examine the impact on production of particles other than sequential Z'

Search for Anomalous Rate in $t \rightarrow \tau v q$



Modified coupling or particle other than W (like H^\pm) may lead to anomalous $t \rightarrow \tau v q$ rate

- Look at di-lepton channel - 5% of $\sigma(t\bar{t})$
- Select events with $\ell\tau_h + 2$ jets ($\ell = e, \mu$)
- Compare $t\bar{t} \rightarrow \ell\tau_h vv + 2$ jets prediction to observation
- Model independent

Search for Anomalous $t \rightarrow \tau v q$ (cont.)

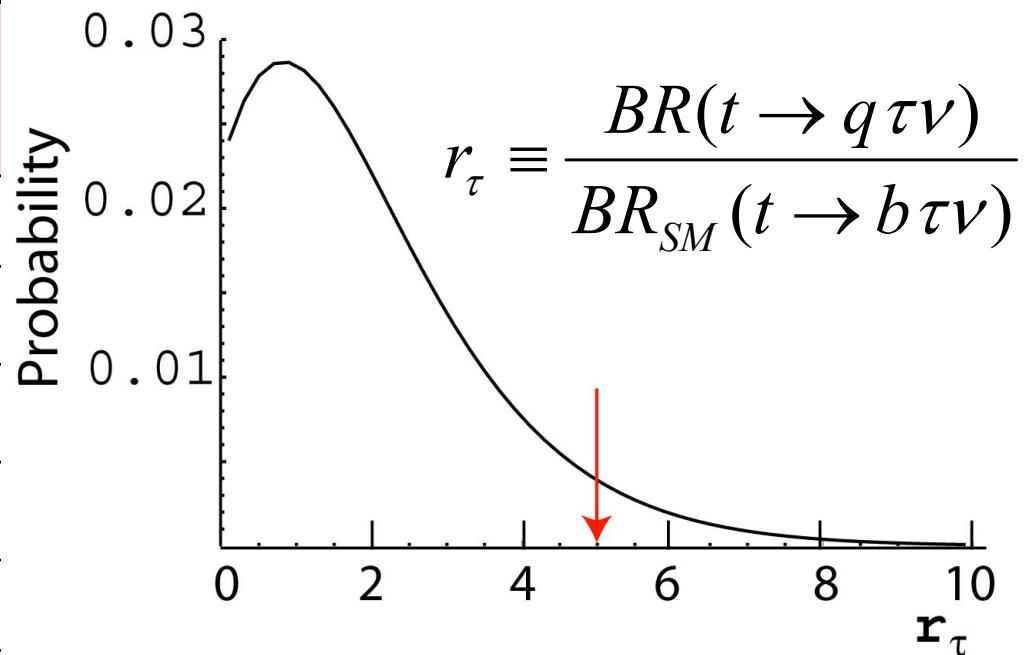
- Backgrounds:
 - W+jet(s)
 - Multi-jet
 - $Z \rightarrow \tau\tau + \text{jets}$; $Z \rightarrow \ell\ell + \text{jets}$, with $e, \mu \rightarrow \tau$ misidentification
 - WW, WZ
- Event cuts
 - Identified τ , $e(\mu)$, ≥ 2 jets
 - $E_T^{\text{jet}1} > 30 \text{ GeV}$, $E_T^{\text{jet}2} > 15 \text{ GeV}$, $p_T(\tau_h) > 15 \text{ GeV}$, $E_T^{e(\mu)} > 20 \text{ GeV}$;
 $E_T > 20 \text{ GeV}$; $H_T > 205 \text{ GeV}$
 - Opposite charge of $e(\mu)$ and τ_h
 - $Z \rightarrow \tau\tau$ removal in region $65 < m_{\tau\tau} < 115 \text{ GeV}$

Total acceptance for $t\bar{t}$: $(0.080 \pm 0.005 \pm 0.014) \%$

H_T : scalar sum of E_T of the selected leptons, jets, and \cancel{E}_T

Result for Anomalous $t \rightarrow \tau \nu q$ Search

Source	Events (num \pm stat \pm sys)
$Z/\gamma^* \rightarrow \tau\tau + \text{jets}$	$0.26 \pm 0.06 \pm 0.05$
jet $\rightarrow \tau$ fakes	$0.75 \pm 0.12 \pm 0.20$
$e \rightarrow \tau$ fakes	$0.08 \pm 0.03 \pm 0.02$
$Z \rightarrow \mu\mu$	0.05 ± 0.03
WW	$0.14 \pm 0.02 \pm 0.03$
WZ	0.02 ± 0.02
Total bg	$1.30 \pm 0.14 \pm 0.21$
Expected $t\bar{t}$	$1.03 \pm 0.06 \pm 0.17$
Observed	2

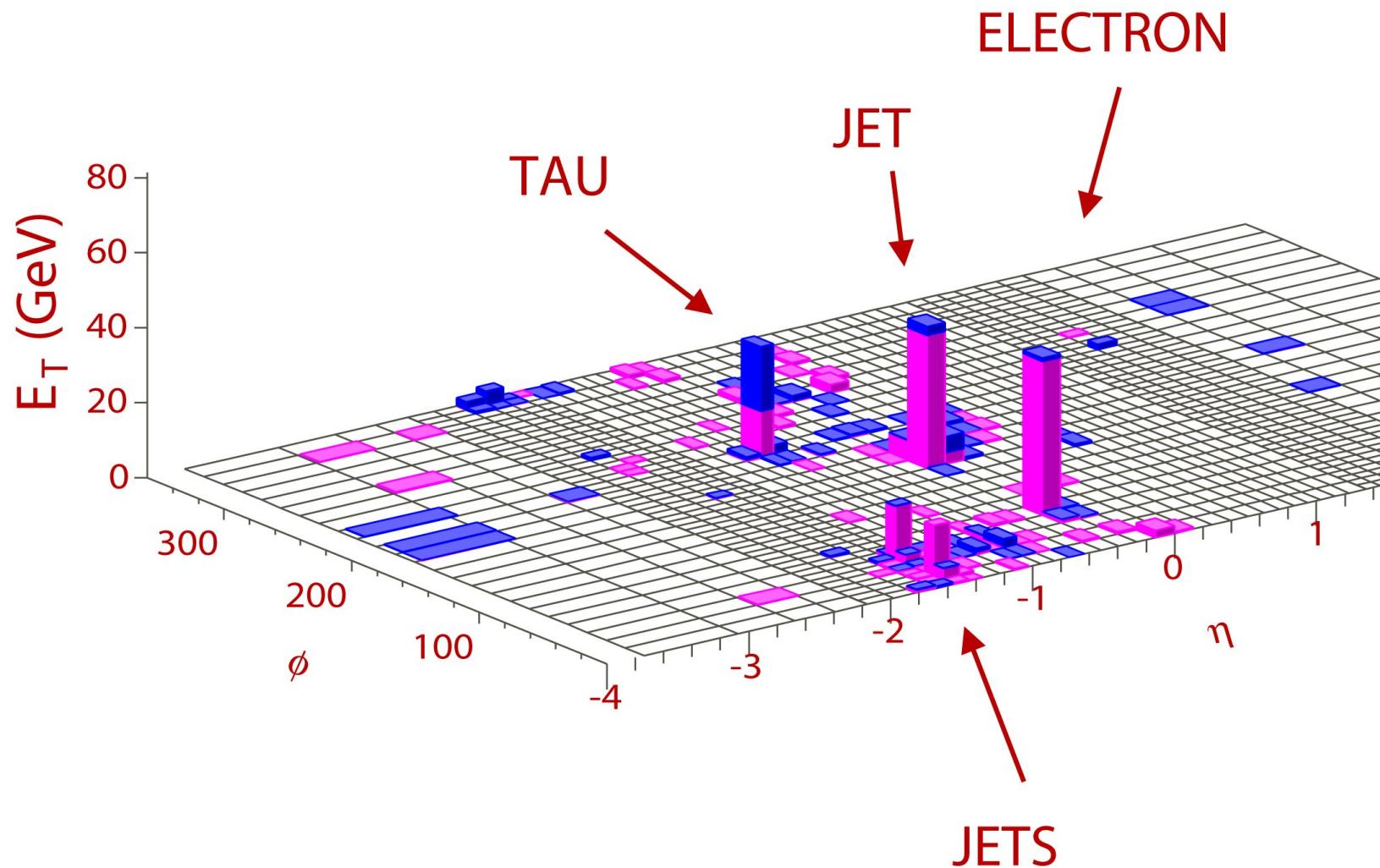


$r_\tau < 5.0$ at 95% CL

Expected improvement with larger data sample

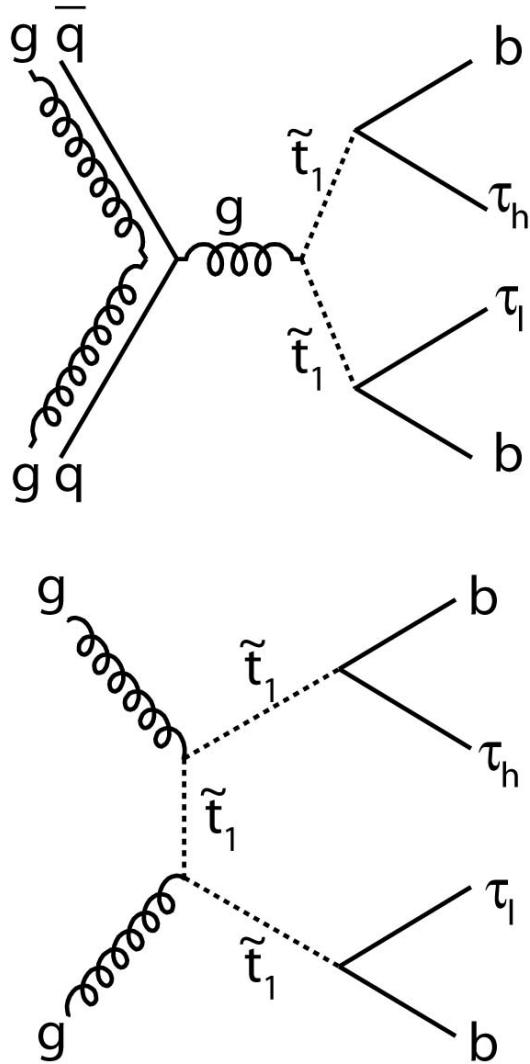
Search for Anomalous $t \rightarrow \tau v q$

$t\bar{t} \rightarrow e\tau_h\nu\nu + 2 \text{ jets}$ candidate event



Prospects for SUSY Searches with Taus

Prospects for RPV Stop Search



Light stop (t_1):

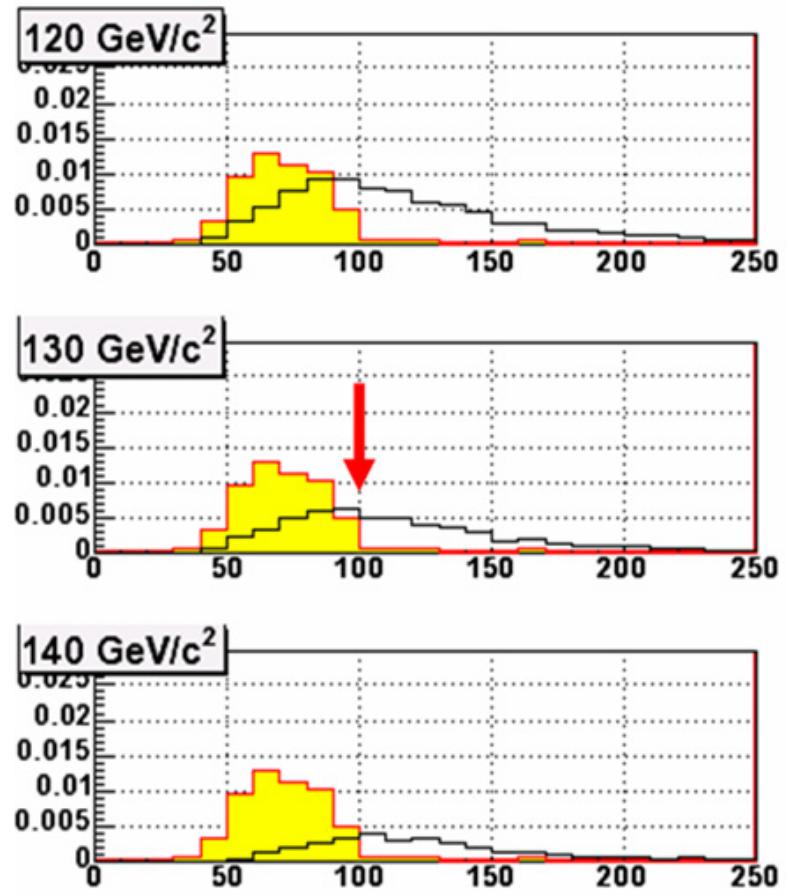
- Potentially smaller mass than other squarks (may be even smaller than m_{top})
- Expected large Yukawa couplings
- Parameter space where stop decays to $b\tau$ is favored
- Pair-produced

Result from Run 1:

- Pre-scaled e trigger
- Limited muon coverage
- Lower cross-section (due to \sqrt{s})

Stop Search: Event Selection

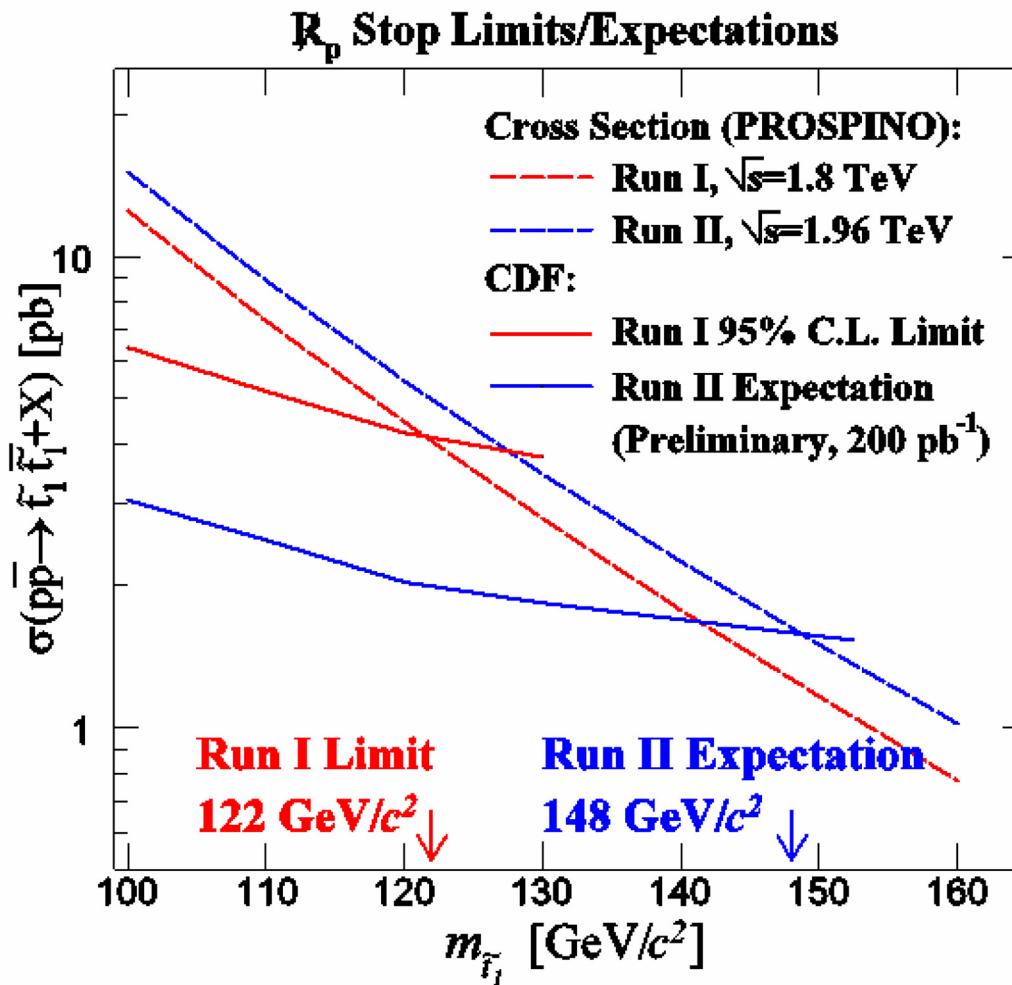
- Final state: $\tau\tau bb \rightarrow \ell\tau_h + 2\text{jets}$ ($\ell = e, \mu$)
- Dominant backgrounds:
 - $Z \rightarrow \tau\tau + \text{jets}$, $W + \text{jets}$
 - Di-boson, $t\bar{t}$
 - Multi-jet
- “Lepton+track” trigger used
- Event selection:
 - Isolated τ_h , ℓ , 2jets ($E_T > 15$ GeV)
 - $p_T^\tau > 15$ GeV, E_T^e (p_T^μ) > 10 GeV
 - $H_T(\ell, \tau_h, E_T) > 100$ GeV
 - $m_T(\ell, E_T) < 35$ GeV
- Expected total bg ~ 2 events



H_T distributions:

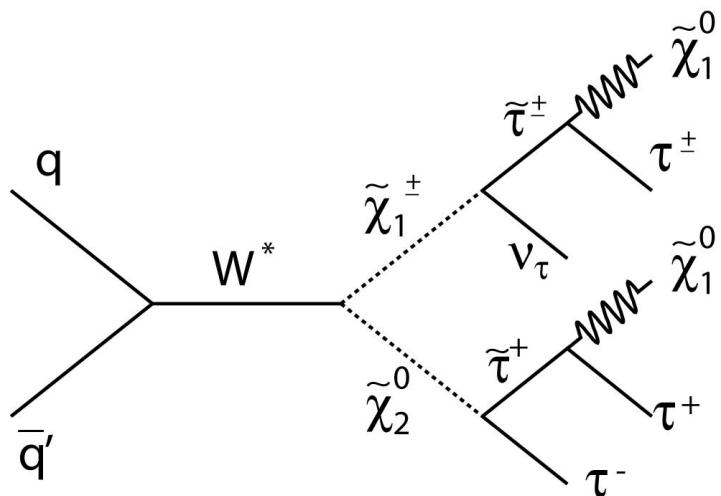
- Signal (open histogram)
- $Z \rightarrow \tau\tau + \text{jets}$ (yellow)

Stop Search: Projected Limit

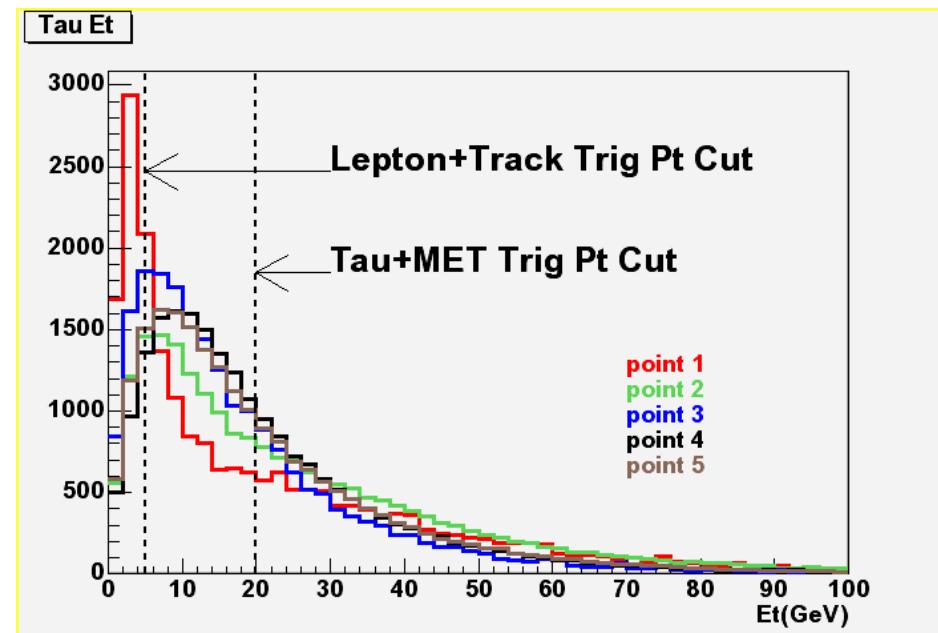
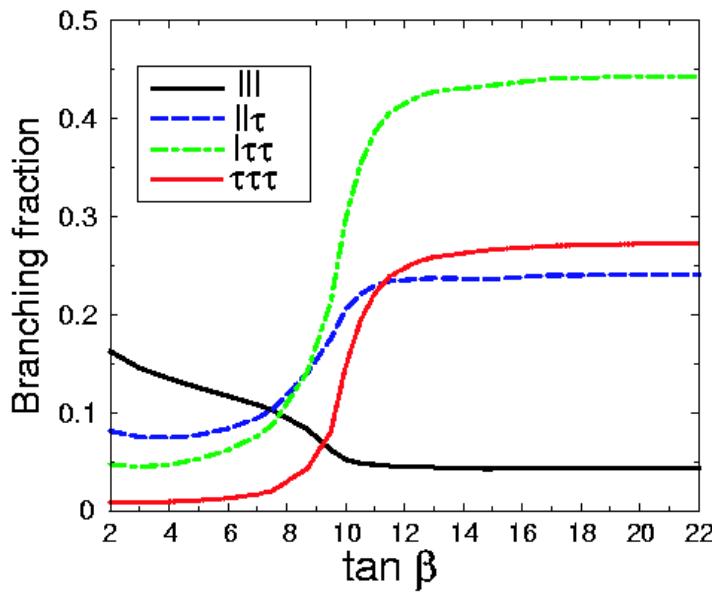


Results using 200 pb^{-1} of data coming soon!

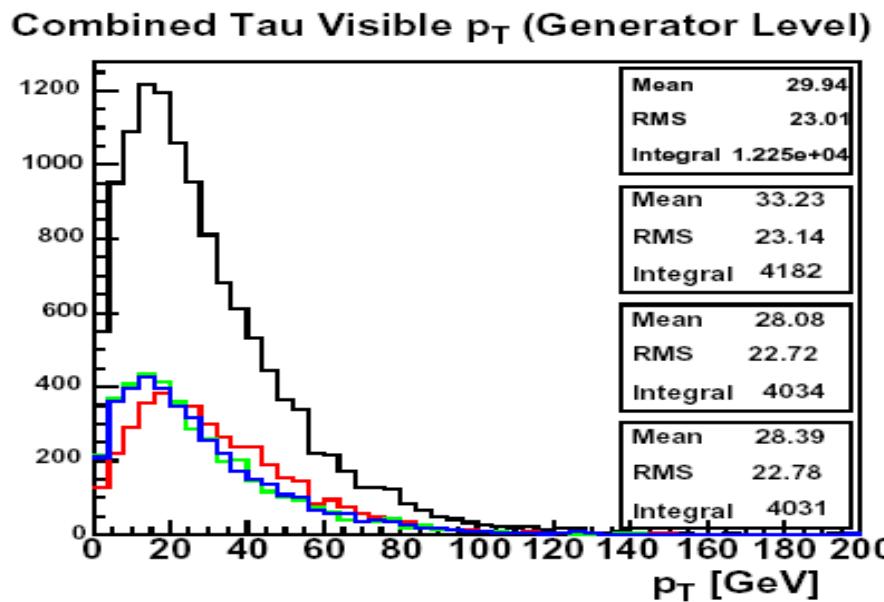
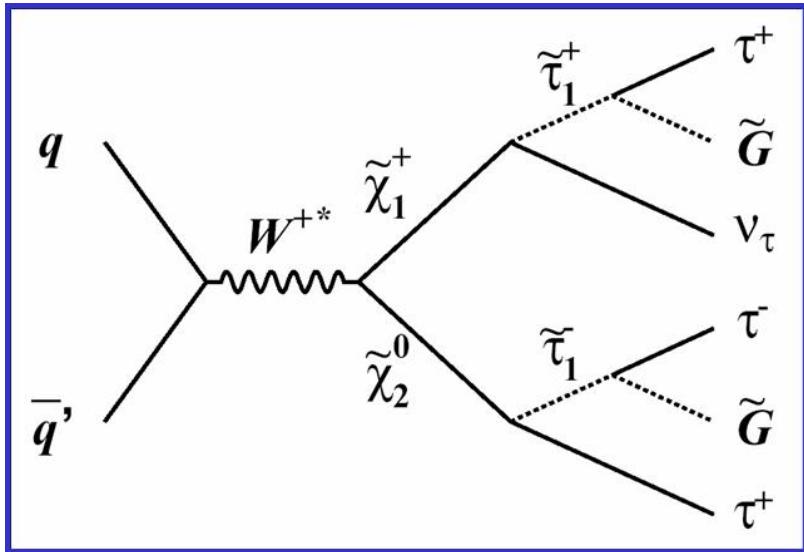
mSUGRA Tri-lepton Search



- Taus in final state dominant at large $\tan\beta$
- Soft taus, still accessible
- Expect up to 2.4 events/fb $^{-1}$ (~ 8 if only two like-sign leptons are required)
- Important, but needs > 1 fb $^{-1}$ data
- Backgrounds are being studied



Prospects for Tri-leptons in GMSB



- Consider case where gravitino is LSP, stau is NLSP
- Similar signature to mSUGRA scenario
- Harder tau spectrum due to small gravitino mass
- Expect ~4-5 events/fb⁻¹
- Work on W+jets suppression needed

Summary and Outlook

- Use of taus expands the physics program at hadronic colliders
- Dedicated set of tau triggers in place
- EW measurements with taus - already a fact
- The search for neutral MSSM $H \rightarrow \tau\tau$ shows real promise
- Prospects for SUSY searches
- Finalize most of the preliminary results using data up to the shutdown
- Other analyses in early (or planning) stages:
 - Charged Higgs, double-charged Higgs
 - Lepto-quarks decaying to $b\tau$

Physics with tau leptons at CDF is strong and results are coming out!